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| journal or publication title | IEEE Photonics Technology Letters |
| volume | 8 |
| number | 2 |
| page range | 248-250 |
| year | 1996-02-01 |
| URL | http://hdl.handle.net/2297/1783 |

# Extended-Range FMCW Reflectometry Using an Optical Loop with a Frequency Shifter

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***Abstract*—We propose a novel method to extend the measurement range of FMCW reflectometry. In this method, an optical loop with a frequency shifter (working frequency $f_{FS}$ Hz) is incorporated in the reference arm of the reflectometry. As a result, the interference signal corresponding to the reference beam that circulates $N$ rounds in the loop appears around $(N \times f_{FS})$ Hz, which means that the signals from different measurement ranges can be detected in different frequency domains. Therefore, it is possible to extend the measurement range. In the experiment, the measurement range is extended from 15 m to 48 m.**

## I. Introduction

FREQUENCY modulated continuous-wave (FMCW) reflectometry is a promising candidate for measuring reflection signals from fiber connectors, packaged optical devices and optical integrated devices [1]–[4]. FMCW reflectometry is mainly composed of a laser source whose optical frequency is lineally chirped in time and a two-beam interferometer shown in Fig. 1. Since the frequency of laser source is modulated by an injection current with a shape of saw-tooth wave, the interference signal between the reference beam reflected by the mirror and the signal beam from the device under test appears at the following beat frequency $f_b$:

$$f_b = 2nLf_m\Delta F/c, \tag{1}$$

where $n$ is the refractive index of the air, $2nL$ the optical path difference (OPD) between the reference and the signal beams, $f_m$ the repetition frequency of the injection current, $\Delta F$ the variation of frequency in chirped range of the injection current and $c$ the light velocity. Therefore, the reflection signal from the device under test can be observed by a spectral analyzer. Because the detective signal is a kind of interference signal, and the maximum of $2nL$ should be equal to the OPD corresponding to the coherence length $L_c$ of the laser source (i.e., $2nL = nL_c$, where the coherence length $L_c$ is measured in air), the maximum of measurement range $L$ is only equal to $L_c/2$.

In this letter, we propose a novel method to extend the measurement range of the FMCW reflectometry and demonstrate the validity of the method.

Manuscript received July 24, 1995; October 13, 1995.

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Publisher Item Identifier S 1041-1135(96)00943-3.

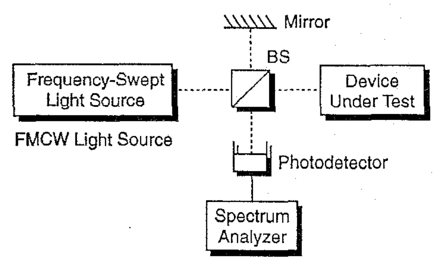


Fig. 1. Basic configuration of FMCW reflectometry.

## II. Configuration

Fig. 2 shows experimental setup of the extended-range FMCW reflectometry. In this setup, optical paths consist of optical fiber instead of air, as compared with Fig. 1. The laser source in the setup is a DFB laser diode emitting at 1.55 $\mu$m, whose coherence length $L_c'$ measured in optical fiber is about 30 m. The laser diode is driven by an injection current with a repetition frequency 100 Hz and a magnitude 8.6 $\mathrm{mA_{p\text{-}p}}$. The variation of frequency in chirped range is about 4.52 GHz. A single-mode optical fiber with length $L$ is connected to the signal arm. The reflection signal from the far end of the fiber (normally 4% in power) is measured by a RF spectrum analyzer with 1 kHz resolution band-width. In order to extend the measurement range of the FMCW, we incorporate an optical fiber loop with a frequency shifter into the reference arm of the reflectometry. An acousto-optical modulator (AOM: HOYA AF–150) is used as the frequency shifter whose working frequency $f_{FS} = 85$ MHz. The insertion loss of the AOM is 8 dB and the total loop loss is about 10 dB. The optical fiber loop length $l$ must be adjusted to be a little shorter than the coherence length $L_c'$ of the laser source (i.e., $l \approx L_c'$), otherwise an insensitive region may occur. In the experiment, the loop length $l$ is taken as 29 m.

By means of incorporating an optical fiber loop with a frequency shifter into the reference arm of the reflectometry, the reference beams are lengthened to $N \times l$, i.e., the integer multiples of the loop length, and have integer multiples working frequency of the frequency shifter. As a result, the interference signal related to the reference beam circulating $N$ rounds in the loop appears around $(N \times f_{FS})$ Hz. Therefore, the signals from different measurement range can be detected in different frequency domain. The measurement range is extended. In this case, the OPD of $2nL$ in Fig. 1 should be replaced by $n'(2L - Nl)$ in Fig. 2. $n'$ is the refractive index

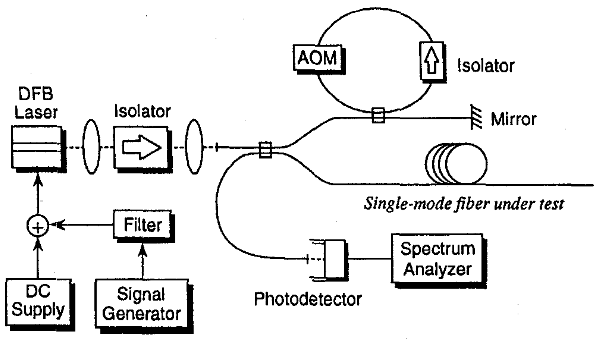


Fig. 2. Proposed extended-range FMCW reflectometry.

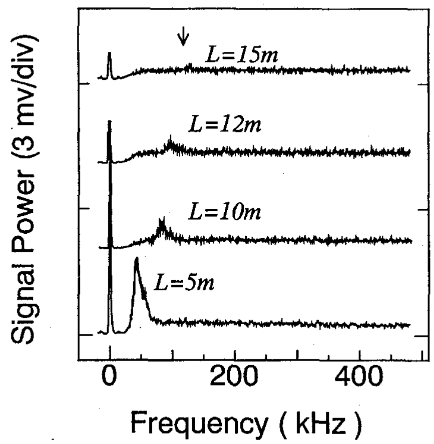


Fig. 3. Signal power spectrum around 0 Hz for $L = 0 \sim l/2$.

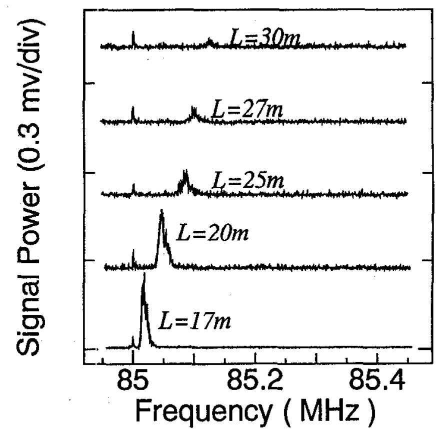


Fig. 4. Signal power spectrum around 85 MHz for $L = l/2 \sim l$.

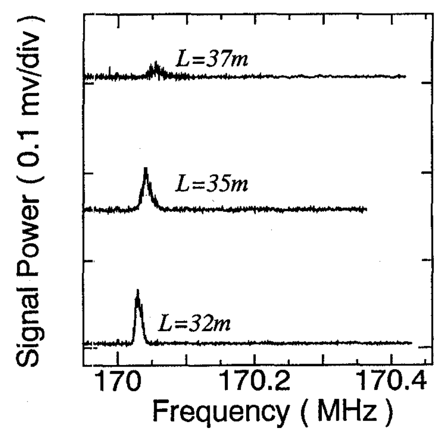


Fig. 5. Signal power spectrum around 170 MHz for $L = l \sim 3l/2$.

of the optical fiber. Then (1) becomes as follows

$$f_b = n'(2L - Nl) f_m \Delta F / c + N \times f_{FS} \quad (N = 0, 1, 2, \ldots, \infty) \tag{2}$$

Because the maximum value of $n'(2L - Nl)$ is equal to the OPD related to the coherence length $L_c'$ of the laser source (i.e. $n'(2L - Nl) = n'L_c' \approx n'l$), the measurable range $L$ is approximately extended to the $(1+N)l/2$. If $N = 0$, the output signals from $L = 0 \sim l/2$ appear around 0 Hz; If $N = 1$, the signals in the range of $L = l/2 \sim l$ appear around $f_{FS}$ Hz; and generally, the signals in the range of $L = Nl/2 \sim (1+N)l/2$ appear around $(N \times f_{FS})$ Hz. The maximum value of $N$, or the measurable extended range $(1 + N)l/2$, is mainly determined by the optical loop loss. It should be noted that the frequency modulation characteristics of laser diodes are affected by (1) the thermal response time of the laser diode, (2) the current dependence of the FM efficiency and (3) the presence of mode hopping due to an optical feedback to the laser diode [5]. Therefore, FM responses of laser diodes show frequency tuning nonlinearity when injection current is a sawtooth wave current. A direct effect of this nonlinearity on detected signals is that the output signal spectrum is broadened, and in turn, the spatial resolution and the identification of two close targets are seriously limited. As demonstrated in reference [3], a simple and effective solution to this problem is to enhance the high-frequency components in the modulation current through a frequency equalizer to improve the frequency tuning nonlinearity.

## III. Experimental Results

In the following experiments, we measure Frensnel reflections at the far end of several optical fibers using the system as shown in Fig. 2. Fig. 3 shows the signal power spectra around 0 Hz for $L = 0 \sim l/2$. The reflection signals become smaller with the increase of the measurement distance, because coherence degree becomes low. The reflection signals can be detected only for $L \leq 15$ m. Failure to observe the signal for $L > 15$ m is due to the OPD ($2n'L$) between two arms of the reflectometry is longer than the coherence length of the laser source. The result indicates that the measurement range of the system without the optical loop with the frequency shifter is shorter than 15 m.

The signal power spectra around 85 MHz for $L = l/2 \sim l$ are shown in Fig. 4. A stronger reflection signal is detected at $L = 17$ m. The occurrence of this signal is due to OPD ($n'(2L - l)$) between two arms is shorter than the coherence length of the laser source, when the reference beam circulates one round in the optical loop. For the same reason, the reflection signals from $L \leq 30$ m as shown in Fig. 4 can

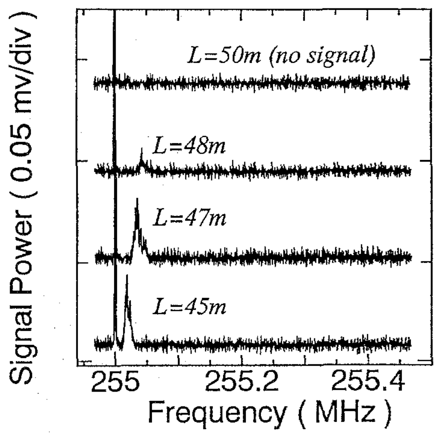


Fig. 6. Signal power spectrum around 255 MHz for $L = 3l/2 \sim 2l$.

also be detected around 85 MHz. Fig. 5 and Fig. 6 show the measured signals power spectra around 170 MHz for $L = l \sim 3l/2$ and around 255 MHz for $L = 3l/2 \sim 2l$, respectively. The reflection signals in the range of $L \geq 48$ m can not be observed because of the large loop loss. From these results, one can find that the measurement range is indeed extended from 15 m to 48 m by using the optical loop with the frequency shifter in the reference arm. The measurement range could be further extended if a low-loss frequency shifter or an optical amplifier is used. The broad reflection signal spectrum probably results from the broad resolution band-width of the RF spectrum analyzer and from the nonlinear optical frequency chirp caused by nonuniform frequency modulation characteristics of the laser [6].

## IV. Conclusion

We have proposed and demonstrated a novel method of extending the measurement range of FMCW reflectometry. In this method, an optical loop with a frequency shifter (working frequency $f_{FS}$ Hz) is incorporated into the reference arm of the reflectometry. As a result, the interference signal corresponding to the reference beam which circulates $N$ rounds in the loop appears around $(N \times f_{FS})$ Hz. We can observe the signals from different range in different frequency domain. The measurement range is extended from 15 m to 48 m. The measurement range should be further extended if an optical loop with low loss is used.

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